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# An Accelerator System for Neutron Radiography

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# An Accelerator System for Neutron Radiography*

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**Abstract.** The field of x-ray radiography is well established for doing non-destructive evaluation of a vast array of components, assemblies, and objects. While x-rays excel in many radiography applications, their effectiveness diminishes rapidly if the objects of interest are surrounded by thick, high-density materials that strongly attenuate photons. Due to the differences in interaction mechanisms, neutron radiography is highly effective in imaging details inside such objects. To obtain a high intensity neutron source suitable for neutron imaging, a 9- MeV linear accelerator is being evaluated for putting a deuteron beam into a high-pressure deuterium gas cell. As a windowless aperture is needed to transport the beam into the gas cell, a low-emittance is needed to minimize losses along the high-energy beam transport (HEBT) and the end station. A description of the HEBT, the transport optics into the gas cell, and the requirements for the linac will be presented.

## INTRODUCTION

The concept of using 10-15 MeV neutrons to image heavily-shielded, low-Z (atomic number) objects has been demonstrated [1]. In order to significantly increase the resolution and decrease the imaging time for neutron radiography, a neutron source with an intensity in excess of $10^{12}$ n/sec is required.

Present-day techniques for accelerator-driven neutron generation that use thin metal windows to separate a pressurized deuterium gas cell from the accelerator vacuum are limited in how much beam intensity can be delivered to the gas due to window heating, thus typically limiting the overall intensity of the neutron source to $\sim 10^{11}$ n/sec.

Recent development efforts at Brookhaven National Laboratory (BNL) and Massachusetts Institute of Technology (MIT) [2] have advanced two "windowless aperture" systems to the point where they provide attractive alternatives to metal windows for pressurized gas cell applications and are enabling technologies for going to much higher deuteron beam intensities.

Utilizing this capability, an effort is underway at Lawrence Livermore National Laboratory (LLNL) to develop an integrated high-energy beam transport (HEBT) and end station design that will be used to specify the beam requirements for a high-intensity deuteron particle accelerator intended for neutron radiography.

Two primary constraints exist in transporting the particle beam to the gas cell. The first, and more important constraint is the beam must be focused into a narrow channel in the high-pressure deuterium gas cell so maximum resolution can be achieved by the imaging system. The second constraint concerns minimizing unnecessary induced and operational radioactivity in the overall machine. While the radiation from the pressurized gas cell will be large, if it is localized in only the gas cell, it is more easily shielded and controlled. To satisfy this constraint, the beam needs to be transported to the gas cell with minimal beam loss in the accelerator and the HEBT.

## DIFFERENTIAL PUMPING AND PRESSURIZED GAS CELL

The present approach is to use a plasma porthole to isolate the 2-3 atmospheres of deuterium gas in the gas cell from the accelerator vacuum. Testing at MIT has shown that a plasma porthole running with argon can effectively plug a 5 mm diameter channel so a $10^{-4}$ Torr vacuum can be maintained while holding over 2 atmospheres of argon in the gas cell 125 mm away [3]. To reduce the gas load to the accelerator further,

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a series of three apertures tubes from 5 to 8 mm in diameter and 115 mm long each provide conductance-isolation between pumpout chambers in the differential pumping section. The combination of the small diameters of the gas cell and the aperture tubes with an overall longitudinal spacing of over 800 mm means the incoming particle beam must be of sufficiently low emittance to be able to be focused through the channel. By using the aperture system in combination with the plasma porthole, we anticipate having a vacuum on the order of $10^{-7}$ Torr in the HEBT. Figure 1 shows the design concept of the end station that was used to develop the accelerator beam requirements.

Constraining the beam emittance so it can be cleanly transported through the aperture system allows us to use a rotating aperture gas cell design as a backup technology for isolating the high pressure gas from the accelerator vacuum. In a rotating aperture system, the beam holes must be as small as possible, and high levels of beam loss can adversely affect the lifetime of the rotating aperture system.

## BEAM STOP

After the deuteron beam passes through the gas cell, it needs to be stopped in such a way that the spatial distribution of neutrons generated in the gas cell is minimally impacted. Conventional approaches for stopping a 9-MeV, 100-300 μA average-current deuteron beam would involve impinging the beam either on a rotating disk, or on a thin water-cooled metal target that is sloped to decrease the power density. Both of these approaches require significant hardware be placed in the flight path of the neutrons that were generated in the gas cell which would adversely affect the distribution of the neutron beam.

We propose an alternative beam stop approach that should be simple, inexpensive, and cause minimal disruption to the neutron beam. The idea is to put a high-Z high-pressure gas behind the deuterium gas cell and use a parallel-flow, pressure-balanced interface that would allow the deuteron beam to go into the high-Z gas and be stopped there with limited gas mixing, as shown in Figure 1. This approach allows the deuterium gas cell to be of a short length, which is needed for high resolution by keeping the interaction region small, and it helps keep the neutrons more nearly monoenergetic as there is a small energy spread imparted on the beam as it goes through the deuterium gas cell.

By using a high-Z stopping gas, cleaning cross-contaminant gases from the other stream would rely on the properties of the respective gases, i.e., deuterium in the high-Z gas could be removed by gettering, where high-Z atoms in the deuterium could be removed by cryo-trapping. The 1-3 kW of average beam power would be removed by a heat exchanger in the high-Z gas recirculation loop.

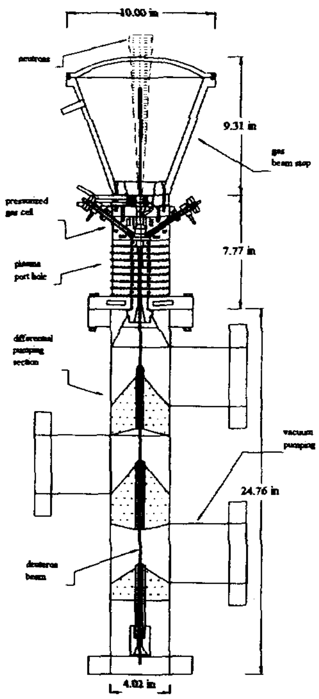


**FIGURE 1.** End station drawing that includes the differential pumping section, plasma porthole, pressurized gas cell and beam stop concept.

## END STATION ACCEPTANCE

The three apertures in the differential pumping section and the aperture of the plasma porthole, combined with the small beam channel needed in the gas cell, place a significant constraint on the beam emittance from the accelerator for this system.

To generate a maximum acceptable emittance value for the end station, the procedure was to generate x-x' and y-y' acceptance parallelograms based purely on the length, spacing, and diameter of the apertures in the reference design. Using basic trigonometry, acceptance parallelograms can be determined both for the geometric acceptance to just transport the beam through the apertures and for the acceptance needed to geometrically put the beam through a thin (1.5 mm diameter) channel in the gas cell. Clearly, the beam channel acceptance is more stringent and is what needs to be met to achieve the desired resolution for the radiography system. The beam channel acceptance as an area in phase space can be determined by:

$$A_0 = \frac{4r_{ap1}r_{sp}}{L+\lambda_{sp}} - \frac{2r_{ap1}\lambda_{sp}(r_{ap1}-r_{sp})}{L(L+\lambda_{sp})}$$

where $r_{ap1}$ is the radius of the entrance aperture, $r_{sp}$ is the radius of the beam spot in the channel, $\lambda_{sp}$ is the length of the spot in the channel, and L is the distance from the first aperture to the beginning of the beam channel.

While this expression gives the area for the channel acceptance in x and y phase spaces, it is not entirely useful as a particle beam distribution rarely looks like a parallelogram in phase space. To obtain the maximum elliptical area ($\alpha_0$) that corresponds to the acceptance parallelogram, it is observed that

$$\frac{\alpha_0}{A_0} = \frac{\pi}{4}$$

for all angles of rotation of the largest ellipse that can be enclosed within a parallelogram. Applying this gives an expression for the maximum elliptical area that can come from the accelerator and still make the desired spot size without scraping the beam on the transport elements:

$$\alpha_0 = \frac{r_{ap1}r_{sp}}{L+\lambda_{sp}}\left\{1-\frac{\lambda_{sp}}{2L}\left(\frac{r_{ap1}}{r_{sp}}-1\right)\right\}\pi$$

Both areas are in mm-mrad if the variables are input as mm. Figure 2 shows a plot of the acceptance parallelogram and the maximum elliptical area. The plot applies for both x-x' and y-y' since the apertures are round.

The maximum elliptical area calculated in this way is an approximation since the plasma porthole will have some effect on the beam, but an estimate of the lens effect due to the plasma shows it is less than 5%.

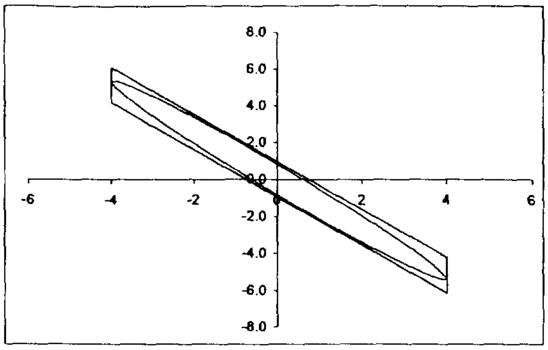


**FIGURE 2.** Plot showing the beam channel acceptance parallelogram and the maximum elliptical area that can be used to achieve the desired beam channel size in the gas cell. The x axis is mm and the y is mrad.

## BEAM FROM AN ACCELERATOR

To this point, the beam spot-size acceptance has been expressed as the largest elliptical area that can be enclosed by the acceptance parallelogram that comes from the beam channel geometry. To relate this to an actual accelerator beam emittance, comparisons will be made between the maximum elliptical area ($\alpha_0$) divided by $\pi$, and the unnormalized, 5*RMS emittance from the accelerator, which contains at least 92% of the density for a Gaussian beam. To cleanly transport the beam through the end station,

$$\varepsilon_{unnormalized,5RMS} < \alpha_0 / \pi .$$

As shown in Figure 3, the longer the beam channel is in the gas cell, the tighter the beam emittance for the accelerator needs to be. The present gas cell design would have a 40 mm long beam channel.

Conveniently, the transport code TRACE3D works in unnormalized 5-RMS emittances, and allows straightforward assessments of potential accelerator designs, at least where ready output beam emittance simulations or data are available. Utilizing output parameters that were generated by PARMILA for a recent linac scoping study [4], TRACE3D was used to design a HEBT,

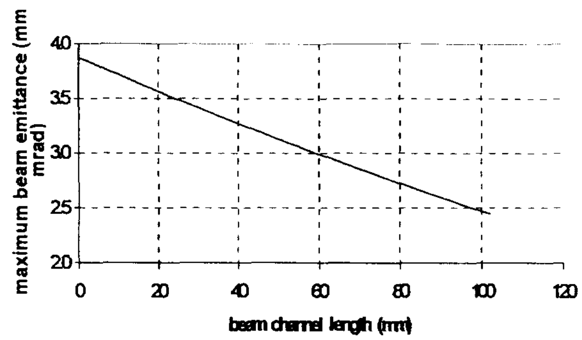


**FIGURE 3.** The maximum unnormalized, 5-RMS beam emittance values needed to obtain 1.5 mm diam. beam channels of different lengths in the gas cell. Plot is for an end station 775 mm long, with and entrance aperture radius of $r_{ap1}$=4 mm, and a beam channel radius of $r_{sp}$ =1.5 mm.

comprised of a magnetic quadruplole and a quadruplole triplet, to transport the beam to the end station. Then, the envelop for a beam having an emittance less than 3.5 mm-mrad was evaluated along the transport line and compared to the apertures in the HEBT and the end station for a good beam transport tune that met the beam channel focusing requirement. The resulting plot, shown in Figure 4, shows the 5-RMS beam envelop as it is transported from the accelerator to the gas cell. From this plot, it is clear that a beam of sufficient quality to meet the beam channel requirement is readily transported through the HEBT and the end station.

## CONCLUSION

To use a particle accelerator for intense neutron radiography, a significant beam-quality constraint is encountered in focusing the beam down to a very tight beam channel in the high pressure deuterium gas cell where the neutrons are generated. For the 40 mm reference design gas cell, the maximum emittance allowable for high-resolution radiography is less than 3.3 mm-mrad unnormalized, 5-RMS.

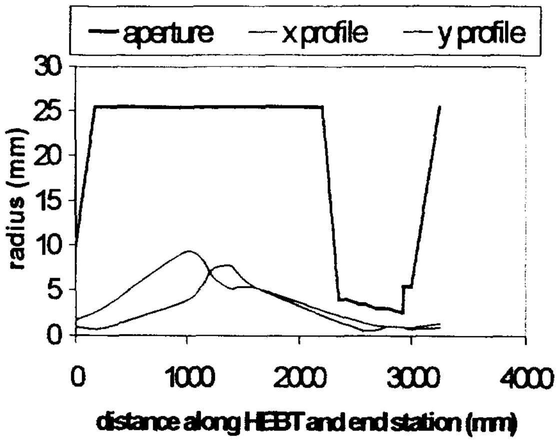


**FIGURE 4.** A plot showing the 5-RMS beam envelop in x and y as the beam moves down the HEBT into the end station and the gas cell where the beam channel requirement needs to be met. The average aperture to beam RMS ratios are 7.94 in x and 4.47 in y.


## ACKNOWLEDGEMENTS

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3. R. Lanza, private communication.
4. R. Hamm, private communication.